18-452/18-750
Wireless Networks and Applications
Lecture 3: Physical Layer
Signals, Modulation, Multiplexing

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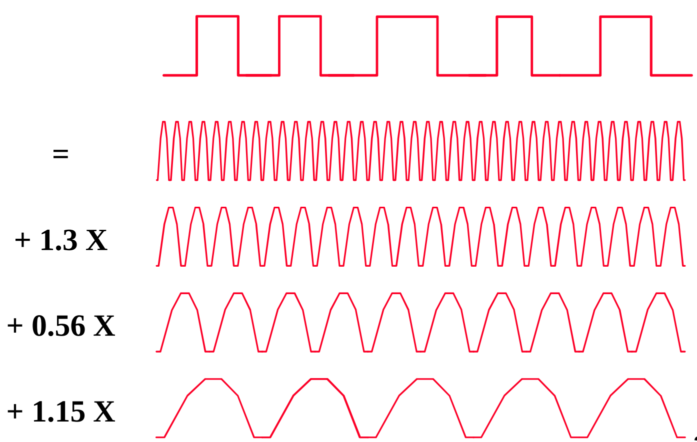
http://www.cs.cmu.edu/~prs/wirelessS18/

Outline

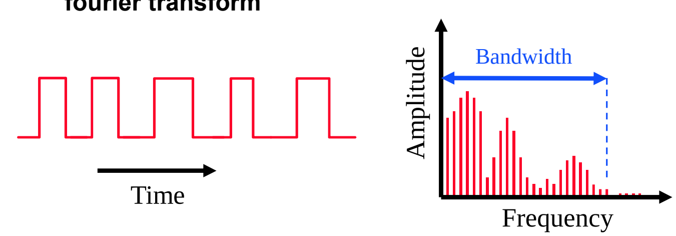
- **RF introduction**
  - » A cartoon view
  - » Communication
  - » Time versus frequency view
- **Modulation and multiplexing**
- **Channel capacity**
- **Antennas and signal propagation**
- **Modulation**
- **Diversity and coding**
- **OFDM**

Signal = Sum of Sine Waves



The Frequency Domain

- **A (periodic) signal can be viewed as a sum of sine waves of different strengths.**
  - Corresponds to energy at a certain frequency
- **Every signal has an equivalent representation in the frequency domain.**
  - What frequencies are present and what is their strength (energy)
- **We can translate between the two formats using a fourier transform**



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- Modulation and multiplexing - review
  - » Analog versus digital signals
  - » Forms of modulation
  - » Baseband versus carrier modulation
  - » Multiplexing
- Channel capacity
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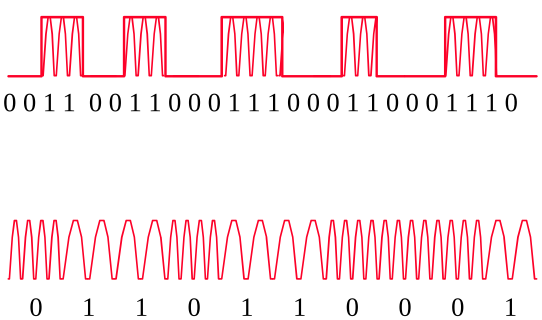
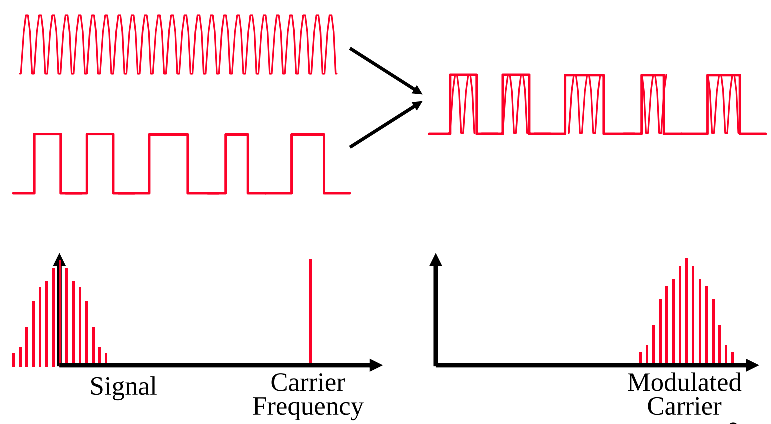
Signal Modulation

- Sender sends a “carrier” signal and changes it in a way that the receiver can recognize
  - The carrier is sine wave with fixed amplitude and frequency
- Amplitude modulation (AM): change the strength of the carrier based on information
  - High values -> stronger signal
- Frequency (FM) and phase modulation (PM): change the frequency or phase of the signal
  - Frequency or Phase shift keying
- Digital versions are also called “shift keying”
  - Amplitude (ASK), Frequency (FSK), Phase (PSK) Shift Keying
- Discussed in more detail in a later the course

Amplitude and Frequency Modulation



Amplitude Carrier Modulation



Analog and Digital Signal Modulation

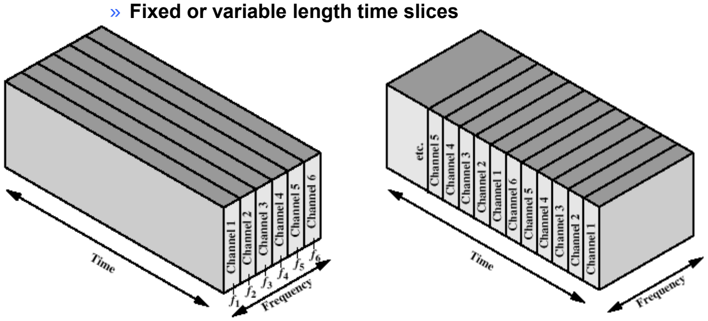
- The signal that is used to modulate the carrier can be analog or digital
  - » Analog: broadcast radio (AM/FM)
  - » Digital: WiFi, LTE
- Analog: a continuously varying signal
  - » Cannot recover from distortions, noise
  - » Can amplify the signal but also amplifies the noise
- Digital: discreet changes in the signal that correspond to a digital signal
  - » Can recover from noise and distortion:
  - » Regenerate signal along the path: demodulate + remodulate

Multiplexing

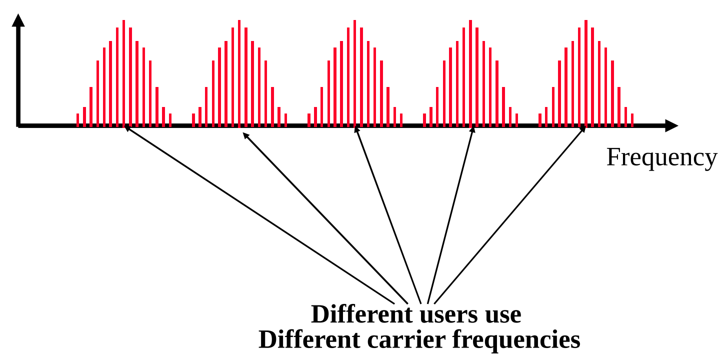
- Capacity of the transmission medium usually exceeds the capacity required for a single signal
- Multiplexing - carrying multiple signals on a single medium
  - » More efficient use of transmission medium
- A must for wireless – spectrum is huge!
  - » Signals must differ in frequency (spectrum), time, or space

Multiplexing Techniques

- Frequency-division multiplexing (FDM)
  - » divide the capacity in the frequency domain
- Time-division multiplexing (TDM)
  - » Divide the capacity in the time domain
  - » Fixed or variable length time slices

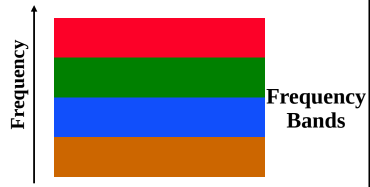


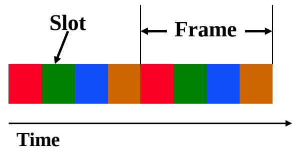
Multiple Users Can Share the Ether



Frequency versus Time-division Multiplexing

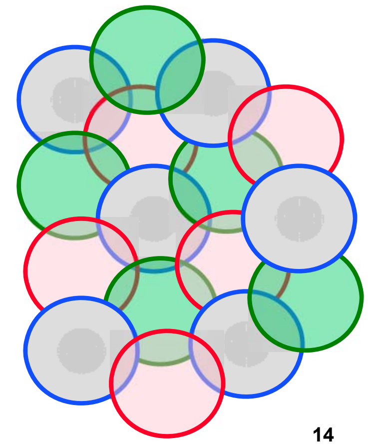
- With frequency-division multiplexing different users use different parts of the frequency spectrum.
  - » I.e. each user can send all the time at reduced rate
  - » Example: roommates
  - » Hardware is slightly more expensive and is less efficient use of spectrum
- With time-division multiplexing different users send at different times.
  - » I.e. each user can sent at full speed some of the time
  - » Example: a time-share condo
  - » Drawback is that there is some transition time between slots; becomes more of an issue with longer propagation times
- The two solutions can be combined.





Frequency Reuse in Space

- Frequencies can be reused in space
  - » Distance must be large enough
  - » Example: radio stations
- Basis for "cellular" network architecture
- Set of "base stations" connected to the wired network support set of nearby clients
  - » Star topology in each circle
  - » Cell phones, 802.11, …



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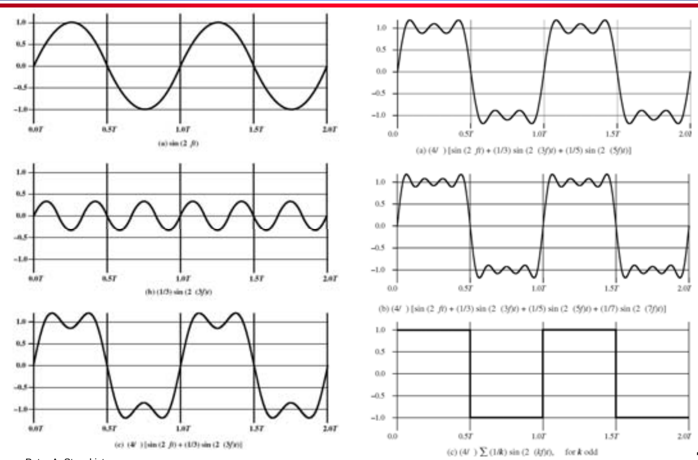
Relationship between Data Rate and Bandwidth

- The greater the (spectral) bandwidth, the higher the information-carrying capacity of the signal
- Intuition: if a signal can change faster, it can be modulated in a more detailed way and can carry more data
  - » E.g. more bits or higher fidelity music
- Extreme example: a signal that only changes once a second will not be able to carry a lot of bits or convey a very interesting TV channel
- Can we make this more precise?

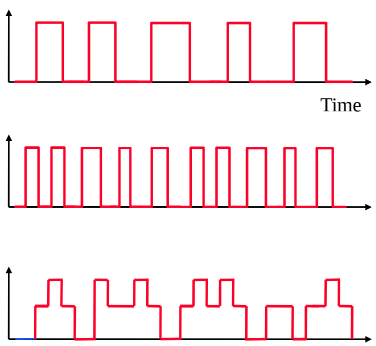
Adding Detail to the Signal



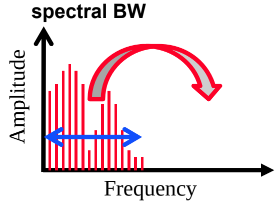
Some Intuition

- Smooth time domain signal has narrow frequency range
  - » Sine wave → pulse at exactly one frequency
- Adding detail widens frequency range
  - » Need to add additional frequencies to represent details
  - » Very sharp edges are especially bad (many frequencies)
- The opposite is also true
  - » Pulse in time domain has very wide spectrum
  - » Same is true for random noise (“noise floor”)
- Implication: modulation has a bid impact on how much (scarce) spectrum is used

Increasing the Bit Rate

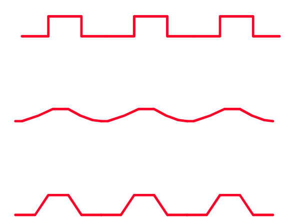


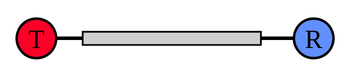
- Increases the rate at which the signal changes.
  - » Proportionally increases all signals present, and thus the spectral bandwidth
- Increase the number of bits per change in the signal
  - » Adds detail to the signal, which also increases the spectral BW



So Why Don’t we Always Send a Very High Bandwidth Signal?

- Channels have a limit on the type of signals they can carry effectively
- Wires only transmit signals in certain frequency ranges
  - » Stronger attenuation and distortion outside of range
- Wireless radios are only allowed to use certain parts of the spectrum
  - » The radios are optimized for that frequency band
- Distortion makes it hard for receiver to extract the information
  - » A major challenge in wireless





Propagation Degrades RF Signals

- Attenuation in free space: signal gets weaker as it travels over longer distances
  - » Radio signal spreads out – free space loss
  - » Refraction and absorption in the atmosphere
- Obstacles can weaken signal through absorption or reflection.
  - » Reflection redirects part of the signal
- Multi-path effects: multiple copies of the signal interfere with each other at the receiver
  - » Similar to an unplanned directional antenna
- Mobility: moving the radios or other objects changes how signal copies add up
  - » Node moves ½ wavelength -> big change in signal strength

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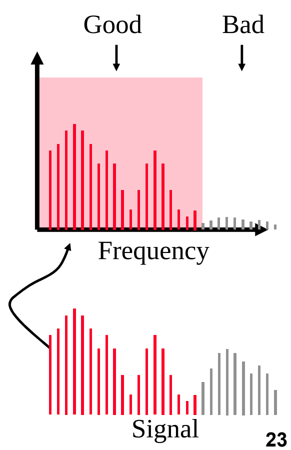
Transmission Channel Considerations

- Example: grey frequencies get attenuated significantly
- For wired networks, channel limits are an inherent property of the wires
  - Different types of fiber and copper have different properties
  - Capacity also depends on the radio and modulation used
  - Improves over time, even for same wire
- For wireless networks, limits are often imposed by policy
  - Can only use certain part of the spectrum
  - Radio uses filters to comply



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Channel Capacity

- Data rate - rate at which data can be communicated (bps)
  - » Channel Capacity – the maximum rate at which data can be transmitted over a given channel, under given conditions
- Bandwidth - the bandwidth of the transmitted signal as constrained by the transmitter and the nature of the transmission medium (Hertz)
- Noise - average level of noise over the communications path
- Error rate - rate at which errors occur
  - » Error = transmit 1 and receive 0; transmit 0 and receive 1

The Nyquist Limit

- A noiseless channel of bandwidth B can at most transmit a binary signal at a capacity 2B
  - » E.g. a 3000 Hz channel can transmit data at a rate of at most 6000 bits/second
  - » Assumes binary amplitude encoding
- *For M levels:* $C = 2B \log_2 M$
  - » M discrete signal levels
- More aggressive encoding can increase the actual channel bandwidth
  - » Example: modems
- Factors such as noise can reduce the capacity

Decibels

- A ratio between signal powers is expressed in decibels

$$\text{decibels (db)} = 10\log_{10}(P_1 / P_2)$$

- Is used in many contexts:
  - » The loss of a wireless channel
  - » The gain of an amplifier
- Note that dB is a relative value.
- Can be made absolute by picking a reference point.
  - » Decibel-Watt – power relative to 1W
  - » Decibel-milliwatt – power relative to 1 milliwatt

Signal-to-Noise Ratio

- Ratio of the power in a signal to the power contained in the noise that is present at a particular point in the transmission
  - » Typically measured at a receiver
- Signal-to-noise ratio (SNR, or S/N)

$$(SNR)_{\text{dB}} = 10\log_{10}\frac{\text{signal power}}{\text{noise power}}$$

- A high SNR means a high-quality signal
- Low SNR means that it may be hard to "extract" the signal from the noise
- SNR sets upper bound on achievable data rate

Shannon Capacity Formula

- Equation: $C = B\log_2(1+\text{SNR})$
- Represents error free capacity
  - » It is possible to design a suitable signal code that will achieve error free transmission (you design the code)
- Result is based on many assumptions
  - » Formula assumes white noise (thermal noise)
  - » Impulse noise is not accounted for
  - » Various types of distortion are also not accounted for
- We can also use Shannon's theorem to calculate the noise that can be tolerated to achieve a certain rate through a channel

Shannon Discussion

- Bandwidth B and noise N are not independent
  - » N is the noise in the signal band, so it increases with the bandwidth
- Shannon does not provide the coding that will meet the limit, but the formula is still useful
- The performance gap between Shannon and a practical system can be roughly accounted for by a gap parameter
  - » Still subject to same assumptions
  - » Gap depends on error rate, coding, modulation, etc.

$$C = B\log_2(1+\text{SNR}/\Gamma)$$

Example of Nyquist and Shannon Formulations

- Spectrum of a channel between 3 MHz and 4 MHz ; SNR_{dB} = 24 dB

$$B = 4\text{ MHz} - 3\text{ MHz} = 1\text{ MHz}$$

$$\text{SNR}_{\text{dB}} = 24\text{ dB} = 10\log_{10}(\text{SNR})$$

$$\text{SNR} = 251$$

- Using Shannon's formula

$$C = 10^6 \times \log_2(1+251) \approx 10^6 \times 8 = 8\text{Mbps}$$

Example of Nyquist and Shannon Formulations

- How many signaling levels are required?

$$C = 2B\log_2 M$$

$$8\times10^6 = 2\times(10^6)\times\log_2 M$$

$$4 = \log_2 M$$

$$M = 16$$

- Look out for: dB versus linear values, $\log_2$ versus $\log_{10}$

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  - » How do antennas work
  - » Propagation properties of RF signals
  - » Modeling the channel
- Equalization and diversity
- Modulation and coding
- Spectrum access

What is an Antenna?

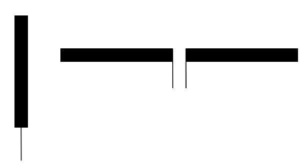
- Conductor that carries an electrical signal and radiates an RF signal.
  - » The RF signal "is a copy of" the electrical signal in the conductor
- Also the inverse process: RF signals are "captured" by the antenna and create an electrical signal in the conductor.
  - » This signal can be interpreted (i.e. decoded)
- Efficiency of the antenna depends on its size, relative to the wavelength of the signal.
  - » E.g. quarter of a wavelength

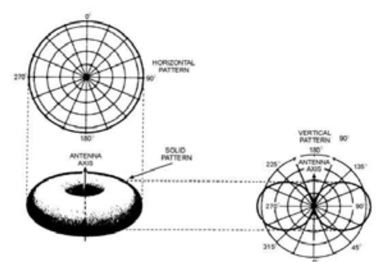
Types of Antennas

- Abstract view: antenna is a point source that radiates with the same power level in all directions – omni-directional or isotropic.
  - » Not common – shape of the conductor tends to create a specific radiation pattern
  - » Note that isotropic antennas are not very efficient!!
    - – Unless you have a very large number of receivers
- Common shape is a straight conductor.
  - » Creates a "disk" pattern, e.g. dipole
- Shaped antennas can be used to direct the energy in a certain direction.
  - » Well-known case: a parabolic antenna
  - » Pringles boxes are cheaper

Antenna Types: Dipoles

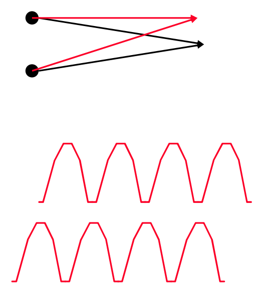
- Simplest: half-wave dipole and quarter wave vertical antennas
  - » Very simple and very common
  - » Elements are quarter wavelength of frequency that is transmitted most efficiently
  - » Donut shape
- May other designs



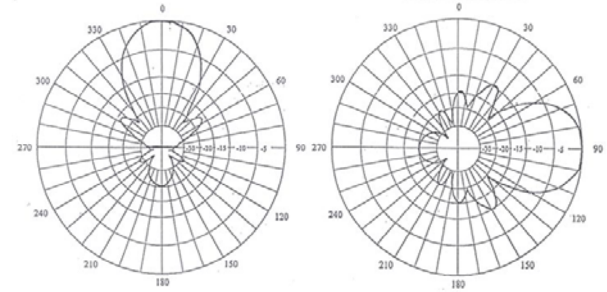


Multi-element Antennas

- Multi-element antennas have multiple, independently controlled conductors.
  - » Signal is the sum of the individual signals transmitted (or received) by each element
- Can electronically direct the RF signal by sending different versions of the signal to each element.
  - » For example, change the phase in two-element array.
- Covers a lot of different types of antennas.
  - » Number of elements, relative position of the elements, control over the signals, …

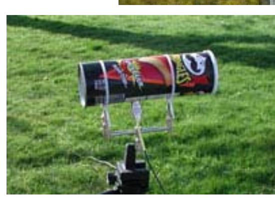


Directional Antenna Properties



- dBi: antenna gain in dB relative to an isotropic antenna with the same power.
  - » Example: an 8 dBi Yagi antenna has a gain of a factor of 6.3 (8 db = 10 log 6.3)

Examples 2.4 GHz



Summary

- The maximum capacity of a channel depends on the SINR
  - » How close you get to this maximum depends on the sophistication of the radios
  - » Distortion of the signal also plays a role – next lecture
- Antennas are responsible for transmitting and receiving the EM signals
  - » The “ideal” isotropic antenna is a point source that radiates energy in a sphere
  - » Practical antennas are directional in nature, as a result of the antenna shape or the use of multi-element antennas
  - » The antenna gain is expressed in dBi